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The effectiveness of plug-in hybrid electric vehicles and renewable power in support of holistic environmental goals: Part 1 – Evaluation of aggregate energy and greenhouse gas performance

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HIGHLIGHTS

- Integration of PHEVs can increase renewable utilization under certain conditions.
- PHEV environmental benefit depends on grid renewable percentage.
- Combined benefits are maximized when PHEV/renewable synergies are realized.
- Additional complementary technologies are still needed to meet environmental goals.

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ABSTRACT

A study that analyzes the effectiveness of plug-in hybrid vehicles (PHEVs) to meet holistic environmental goals has been performed across the combined electricity and light-duty transportation sectors. PHEV penetration levels are varied from 0 to 60% and base renewable penetration levels are varied from 10 to 45%. Part 1 of the study focuses on CO_2 emissions, fuel usage, and the renewable penetration level of individual and combined energy sectors. The effect on grid renewable penetration level depends on two factors: the additional vehicle load demand acting to decrease renewable penetration, and the controllability of vehicle charging acting to reduce curtailment of renewable power. PHEV integration can reduce CO_2 emissions and fuel usage and increase the aggregate renewable energy share compared to the no-vehicle case. The benefits of isolated PHEV integration are slightly offset by increased CO_2 emissions and fuel usage by the electric grid. Significant benefits are only realized when PHEVs are appropriately deployed in conjunction with renewable energy resources, highlighting important synergies between the electric and light-duty transportation sectors for meeting sustainability goals.

1. Introduction and background

1.1. Introduction

Concerns regarding the impact of energy usage on the physical and economic environments have motivated the development of broad-context sustainability goals. These goals include promoting energy security, mitigating the effects of air pollution, climate change, and resource depletion. Each resource sector has set individual sustainability goals for their respective performance in order to contribute towards reaching the larger sustainability goals.

The electricity sector in many countries and states has set targets for meeting increasing fractions of electricity demand with renewable resources to promote a shift towards a low-carbon, low-pollutant emission grid mix. For example, California is mandated to provide 33% of all retail sales of electricity from renewable resources by the year 2020. Other states in the U.S. also aim to reach similar goals to larger or smaller extents [1]. Hawaii has set one of the most aggressive targets at 40% renewable electricity by 2030 [1,2]. Each region will attempt to make the best use of its local renewable resource types to meet these goals while still providing satisfactory electrical service to all customers.

The transportation sector in many regions also has individual sustainability goals. Reductions in greenhouse gas emissions, criteria pollutant emissions, and energy consumption can be achieved through the use of alternative fuels to meet the transportation demand, as measured in vehicle miles traveled (VMT). For

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example, California Executive Order B-16-2012 aims to put 1.5 million zero emission vehicles (ZEVs) on state roads by 2025 [3]. For ZEVs to be effective, fuel supply chain impacts, infrastructure impacts, and consumer demand behavior must be considered.

Unlike the diverse sources of energy used for electricity generation, however, the light-duty transportation sector has historically relied on a single primary energy source in the form of petroleum, limiting options for meeting sustainability goals. This has forced transportation to rely solely on energy efficiency as a means of reducing energy consumption and GHG emissions. A shift toward alternative fuels, specifically electricity, grants the light-duty transportation sector a degree of flexibility beyond simple efficiency improvements. This shift, however, will place an extra burden on the electric power system in the form of increased load. If implemented inappropriately, plug-in electric vehicles (PEVs) may impede the ability of the electricity sector to meet its own sustainability goals and reduce the ultimate environmental benefits of PEVs. But, if implemented appropriately, this integration can create synergies that aid each sector to extents that are not possible individually.

In California, the total transportation sector composes about 39% of the state's total energy consumption. California also consumes 11.8% of the transportation sector energy of the entire U.S. [4]. This mix is dominated by the use of gasoline and diesel for light and heavy duty road vehicles, but also includes fuel use in other vehicles such as ships and aircraft. Correspondingly, if a significant fraction of future vehicles rely on electricity, there may be a significant increase in electric load that must be managed within the constraints of the electric power system. Compounding on this effect is the fact that the VMT demand of the light-duty transportation sector is expected to grow with population in the same manner as the electric load demand [5]. One possible implication of the integration of electricity and transportation may be difficulty for the electricity sector to meet its renewable energy procurement goals. Renewable portfolio standards are based on the percentage of retail electricity sales supplied by renewable resources. With a significant increase in the electric load demand beyond standard growth projections due to the addition of transportation, even more intermittent renewable capacity will need to be installed and managed to meet RPS targets.

For the electrification of the light-duty transportation sector to be holistically beneficial, it must be implemented in a manner which provides a benefit to the electric power system, and provides affordable, reliable, and timely electric fuel for vehicle drivers. The use of "smart charging" strategies for plug-in electric vehicles (PEVs) offers one method of integration that should be mutually beneficial. The extent of these benefits is examined in this study. Plug-in hybrid electric vehicles (PHEVs) are a subset of PEVs which use electricity stored in a battery and a chemical fuel stored in an on-board tank for propulsion. The battery can be charged by 'plugging-in' the vehicle to the electric grid. Electric drive is typically prioritized, with the chemical fuel being used when the battery is depleted or when additional power may be required. In this study, PHEVs using gasoline as the chemical fuel are considered since these vehicles can take advantage of the environmental benefits of electric drive while still providing sufficient range for all consumers to meet their transportation needs.

1.2. Background

Due to increasing interest in the development of alternative fuel vehicles over the past few years, much work has already been conducted to explore the interaction between plug-in electric vehicles and the electric grid.

A study performed by Jansen [6] provided some insight into the increase in the electric demand for the state of California due to plug-in vehicles, using a 40% penetration of PHEVs with a 40 mile all-electric range and uncontrolled charging behavior. The total electric load demand of a typical day was found to increase by 5–10% between the hours 9 am to 9 pm, and suggested an increased reliance on peaking power plants during this period. Similar parameters analyzed in New York show smart charging can reduce electricity system costs [7].

The integration of plug-in electric vehicles can also affect criteria pollutant emissions from conventional power plants. A previous study found that PHEV integration would increase grid-average CO and non-methane organic compound emission intensities by 4% and 7% respectively between 9 am and 9 pm, and reduce the NO_x average emission intensity by about 3% between 5 pm and 9 pm. The total emissions of criteria pollutants of stationary and mobile sources combined, however, is expected to decrease as increases in power plant emissions are offset by reductions in mobile source emissions due to lower gasoline use. The translation to improvements in air quality is dependent on the time of day when emissions are decreased [8].

The facets of this interaction within the context of renewable integration have also been addressed to some extent.

Dallinger [9] conducted a study which examined the role of grid-connected vehicles in improving the integration of renewable energy sources in California and Germany. This study compared the regional differences between these systems, as well as the effect of different charging strategies: last trip charging, time of use tariff charging, and demand side management charging. The study found that last trip charging resulted in a reduced electric driving share, increased net load ramp rates, and contributed only a small amount towards balancing renewable resources. Time-of-use tariff charging was found to balance renewable power generation only if the net load profile was regular and periodic. With non-periodic renewable generation, time-of-use tariff charging did not provide enough flexibility to gain benefits. Demand-side management charging was found to reduce net load ramp rates and was able to provide the most contribution towards managing intermittent renewable resources. This strategy was found to be more effective in California compared to Germany due to the characteristics of the load and renewable generation in that region.

Denholm [10] examined the benefits of an interaction between plug-in vehicle integration and solar PV deployment, specifically. This study found that mid-day charging of electric vehicles with solar PV can increase the amount of miles traveled using low-cost electricity and reduce the required battery size in plug-in vehicles. PHEV charging was found to provide a flexible source of electric load that can maximize the use of solar PV, especially during low load periods. Solar PV was also found to meet the burden of increased peak generation requirements due to mid-day charging. Overall, the study concluded that solar PV and PHEVs have important complementary characteristics. A case study in Brazil by Soares [11] examined the use of plug-in electric vehicles to maximize intermittent renewable integration. This study was conducted in anticipation of large wind power capacity that will be installed in the region in future years. It was discovered that a fleet of 500,000 PHEVs by 2015 and 1.5 million PHEVs by 2030 with overnight charging would allow the region to eliminate the onset of excess wind generation and reduce the need to significantly modify the electric power system.

Querini et al. show that GHG emissions are almost always reduced for PEVs utilizing renewable electricity compared to traditional gasoline or diesel vehicles, regardless of the manufacturing location or manufacturing techniques of the renewable technologies [12]. However, the study does not consider

vehicle charging profiles or actual electric grid operating characteristics.

More studies regarding the development of optimization algorithms for vehicle charging within the context of renewable resources are outlined by Richardson [13], with respect to wind, solar, and biomass individual interactions with plug-in hybrid vehicles. Additional studies examining V2G capability in the context of renewable integration have also been considered [14–16].

Many specific aspects of the interaction between plug-in vehicles and the electric grid have been examined in the literature, even within the context of renewables. To date, however, there has only been little insight into this interaction within the context of meeting holistic sustainability goals. The majority of studies thus far have focused on PHEVs only as a complementary technology to the grid. Additionally, while the impact of PHEVs on the net load characteristics has been examined, little explicit insight has been given into the impact of these changes on the design and operation of load-balancing resources on the electric grid. The analysis herein aims to provide detailed insight into both of these aspects.

2. Model description and approach

2.1. Model description

2.1.1. The HiGRID model

This analysis utilizes the Holistic Grid Resource Integration and Deployment (HiGRID) model developed at the University of California, Irvine [17]. This tool makes use of renewable generation, dispatchable load, balance generation, and cost of generation modules to determine the technical and economic sensitivities of the utility grid to changes in the electric resource mix and the design of load-balancing generators, within the constraints of reliability requirements and generator capabilities. The model outputs the hourly generation profile of each generator in California, from which numerous characteristics including electricity cost, GHG emissions, fuel use, and capacity factor can be garnered. Specifically, the HiGRID tool makes use of 4 distinct modules, presented in Fig. 1 and described in brief as follows:

2.1.1.1. Renewable generation module. This module takes the capacity of different renewable resources as an input, and uses models of each type to determine the time-resolved profile of power generation and power delivered to load for each resource type. The resource types included are Solar PV (fixed, 1-axis tracking, 2-axis tracking, concentrated), Wind, Geothermal (binary and flash), Biomass/Biogas, and Small Hydropower. More details on these modules are presented by Eichman [17]. The costs associated with utilization of these resource types is also calculated and factored into the cost of generation module. The generation profile of the combined renewable resource mix is composed and fed into the dispatchable load module.

2.1.1.2. Dispatchable load module. The dispatchable load module takes the time resolved electric demand profile and aggregate renewable generation profile as inputs to compose the net load profile. This module dispatches complementary technologies and loads in response to the behavior of the net load profile or the behavior of balance generators through an iterative process, within the operating constraints of each technology. Included in this module are models for hydroelectric generation, energy storage (thermal and electric), demand response, electric vehicle charging, and hydrogen production/storage. The option for some of these technologies to meet ancillary service requirements for the grid such as spinning reserve and regulation capacity is also available. After all selected technologies are dispatched, the adjusted net load profile and the remaining portion of ancillary services which balancing generators must meet is produced and fed into the balance generation module. More details can be found in Ref. [17].

2.1.1.3. Balance generation module. The balance generation module determines the sizing and dispatch of base-load, load-following, and peaking generation that is required to meet the adjusted net load profile and remaining ancillary services, within the performance capabilities of different generator classes. Base-load generators such as nuclear and coal power plants are dispatched on an installed capacity and monthly capacity factor basis that includes planned outages, and have flat operating profiles within each month. Load-following and peaking generators are dispatched to meet the remainder of the adjusted net load profile. Each of these classes of generators has performance limitations including minimum operation time, ramping limitations, part-load operation range, and generator size. Additionally, the maximum and minimum number of load-followers and peaking generators are also considered. The algorithm for dispatching these generators and a further description of their parameters are presented in detail by Eichman [17]. The operation of balance generators determined in this module can also be re-fed back into the dispatchable load module to allow technologies to respond specifically to certain aspects of the balance generator fleet (i.e. number of peaking generators) in an iterative process.

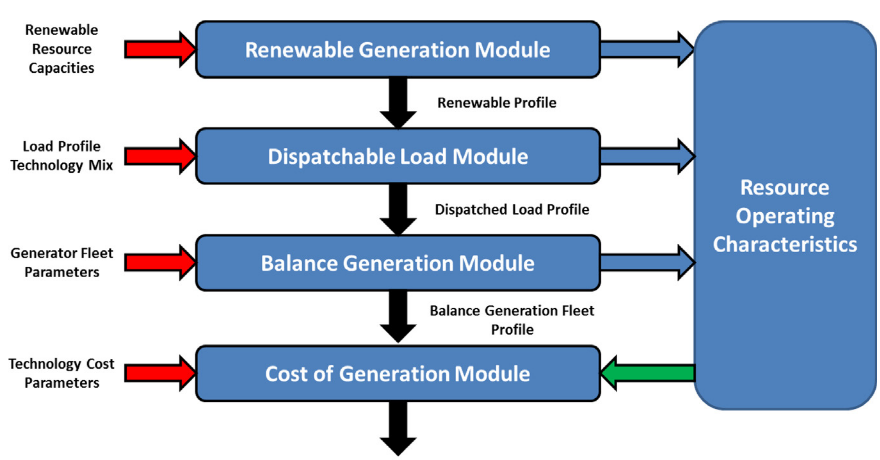

Fig. 1. HiGRID model flowchart.

2.1.1.4. Cost of generation module. Once all of the installed capacities, operational characteristics, and resource consumption of all of the different types of technologies considered have been computed, these measures are fed as inputs into the cost of generation module. This module is based in part on the California Energy Commission (CEC) model for determining the Levelized Cost of Electricity (LCOE) and has been developed further to include a wide range of technologies and unique operation methods. A more detailed description is presented by Eichman in Ref. [17].

2.1.2. Electric vehicle charging

Electric vehicle energy usage is modeled using a tool that accounts for the electricity and fuel use associated with plug-in hybrid electric vehicles (PHEV) constructed by Li Zhang [18,19] as shown in Fig. 2. The two part model determines how vehicles are operating and charging. Inputs include: vehicle type, miles per gallon, energy consumption per mile, battery depth of discharge, vehicle range, charging power, charging location and charging strategy. The model interfaces with National Household Travel Survey (NHTS) data to provide realistic trip information. Using the inputs and trip data, electrical and fuel consumption profiles can be determined.

Driving distances or durations may require that the vehicles operate using the gasoline engine. The model ensures that all trips can be made either on electricity or gasoline with a goal to maximize the portion of miles driven using electricity.

The model can consider two different charging locations and their combination, which includes home-only and both home and work. This assumes that the opportunity exists for a vehicle owner to charge the vehicle at either home or home and work, respectively.

Additionally, three charge strategies can be explored: (1) Immediate charging (when vehicle owners plug their car in immediately when they arrive to their destination and begin charging at maximum power until the vehicle is completely charged); (2) Delayed charging (when vehicle owners do not immediately charge their vehicles when they arrive to a destination but rather at the latest possible time such that they receive a full charge before they leave); and (3) Smart charging (when vehicle owners rely on a control signal to determine when the vehicle will charge). The control signal can take a variety of forms including a utility rate structure (i.e., \$ MWh^{-1}), the Automatic Generation Control (AGC) signal from the grid (i.e., signal used to control regulation resources), or any other signal that can establish priority for charging at different times.

The electric vehicle model is added into the HiGRID model to look at the effect of electric vehicle penetration, charge location and charge strategies on the grid. The combined model is part of the Spatially and Temporally Resolved Energy and Environment Tool (STREET) modeling methodology developed at the Advanced Power and Energy Program.

2.2. Scenarios for study

In this study, the electricity and transportation systems of the state of California are used as the object of analysis. California currently has set aggressive deployment goals for zero-emission vehicles and renewable power installations. California also has a large population that contributes to high electric total load and light-duty transportation demands. The state also has access to a variety of renewable resources. These characteristics make it ideal for examining multi-sector interactions. The year 2005 is used as the representative year for all of the datasets input into the models for this study.

2.2.1. Control parameters

In order to examine the benefits and disadvantages of integrating transportation and the electric grid, a number of scenarios are examined.

2.2.1.1. Base renewable penetration. This refers to the percentage of the total electric load that is served by renewable energy without any interface with transportation (i.e. no PHEVs). Each base renewable penetration increment corresponds to given capacities of installed renewable resources including solar PV, solar thermal, wind, geothermal, biomass, and small hydropower. Therefore, the effect of interfacing with PHEVs can be determined for fixed renewable capacities to display benefits or disadvantages more clearly.

The Base Renewable Penetration is defined as the ratio of the amount of renewable energy delivered to load (taking into account losses and curtailment) to the total energy of the load. For reference, as of 2013, California stands at roughly 20% base renewable penetration with a goal of 33% by 2020 [20]. The mix of renewable

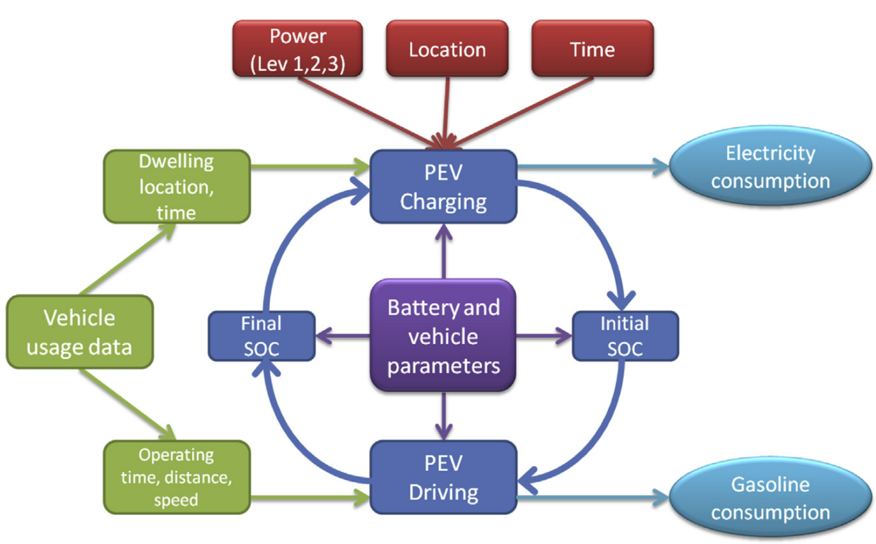

Fig. 2. PHEV operating and charging model.

resources as a function of base renewable penetration level is presented in Fig. 3.

The renewable deployment curve was developed using the specifications for the percentage of energy delivered by each renewable resource in the California Public Utilities Commission's 33% RPS Implementation Preliminary report [21]. The figures specified in this report, however, did not take into account the effects of base load generation, potential renewable curtailment, and the presence of reliability margins. Therefore, the capacities specified in the report were adjusted to meet the specified energy percentage served by each type of renewable resource. This produced a slightly different renewable deployment curve from that used by Tarroja [22], which also used the same report but did not have any uninterruptible base load capacity. Above the 33% renewable penetration level, the renewable mix by energy was assumed to be constant. Further, the range reaches its maximum at a 63% base renewable penetration level, since the presence of base-load capacities hinder the use of many renewable types to serve the load [17,23]. Nuclear power capacity was assumed to be constant across all scenarios, whereas coal power capacity was set to decrease with renewable penetration in reflection of current trends in California. The progression of the base load coal capacity is an extrapolation of the coal generation trends from 2005 to 2011 displayed by the California Energy Commission Total Electricity System Power [24]. The energy delivered is converted to capacity using representative coal plant capacity factors from eGRID [25]. Coal capacity is set to reach zero by the 33% base renewable penetration level.

2.2.1.2. PHEV penetration. This refers to the percentage of the total light duty passenger vehicles in the state that are PHEVs. It is important to note that this penetration number does not necessarily correspond to the fraction of electric vehicle-miles-traveled in the state. Since PHEVs have a limited electric range, miles from any trip exceeding this range will be fueled by gasoline. The PHEV penetration levels considered are shown in Table 1.

It is important to note that the California initiative to deploy 1.5 million ZEVs by 2025 [3] would amount to roughly 6.3% of the projected on-road light duty fleet in that year. Assuming 20% ZEV sales growth per year in line with California Air Resource Board projections, 15% ZEV penetration will not be reached until roughly 2030. As a result, 15% PHEV penetration and 40% electricity renewable penetration (per Hawaii initiative) appears to be a reasonable estimate for the year 2030. Due to the inherent slow turnover rate in on-road vehicle fleets, any PHEV penetration higher than 15% appears unlikely before 40% renewable penetration is reached in California; regardless, the analysis herein spans all possibilities.

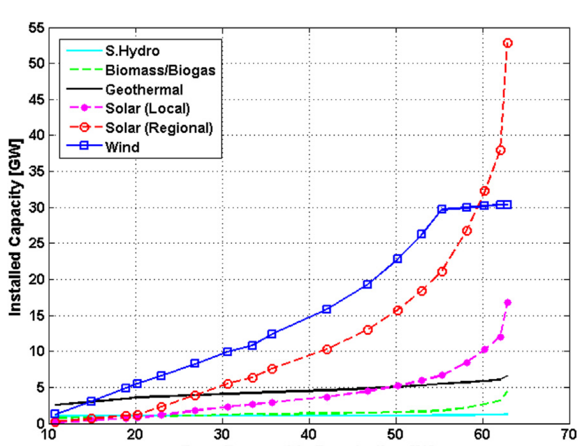

Fig. 3. Renewable mix vs. base renewable penetration level.

Table 1
Number of vehicles at different PHEV penetration levels.

PHEV penetration [%]	Number of vehicles
1	211,148
2	422,297
3	633,446
4	844,595
5	1,055,744
10	2,111,488
15	3,167,232
20	4,222,976
25	5,278,720
30	6,334,464
35	7,390,208
40	8,445,952
45	9,501,696
50	10,557,440
55	11,613,184
60	12,668,928

To be consistent with the load data used in the electric grid module, the total vehicle population of the year 2005 is used for reference. In this study, the all-electric range of the PHEVs is assumed to be 35 miles. This study also assumes that the entire light-duty VMT represents passenger cars with normal household utilization. Additionally, the use of 'smart' charging dispatch from Zhang [18,19] and Eichman [23] is implemented. This charging strategy assumes that the electric vehicle charger receives information about the behavior of the net load profile over the entire window for which the vehicle is to be charged. The charger will then optimize the charging profile to complement that information.

A home-charging infrastructure is assumed to be in place, with 'Level 1' 1.44 kW chargers. This assumption is based on the fact that light-duty vehicles spend about 75% of their residence time at home, and only 14% at the workplace [18,26]. Therefore, the window over which the smart-charging profile can be optimized is much larger with home charging, whereas work charging may only provide limited additional flexibility [19]. Additionally, modern detached homes already have the infrastructure necessary to accommodate Level 1 vehicle charging. Expansion of the charging infrastructure to workplaces and activity areas is possible, but may cause significant increases in infrastructure cost compared to the incremental benefit gained [19].

3. Results and analysis

3.1. Energy metrics and CO_2 emissions

Model results simulate the effect of PHEV integration on the consumption of fossil fuels, renewable energy, and the emissions of CO_2 from the perspective of the combined electricity and light-duty transportation sectors.

3.1.1. Behavior of the grid renewable penetration level

A surface plot showing the change in the renewable penetration level from the base value with the addition of PHEVs is shown in Fig. 4 with an inset in Fig. 5.

Recall that the definition of renewable penetration is:

$$\text{Rpen}[\%] = \frac{E_{\text{Ren,delivered}}}{E_{\text{load}}} \times 100$$

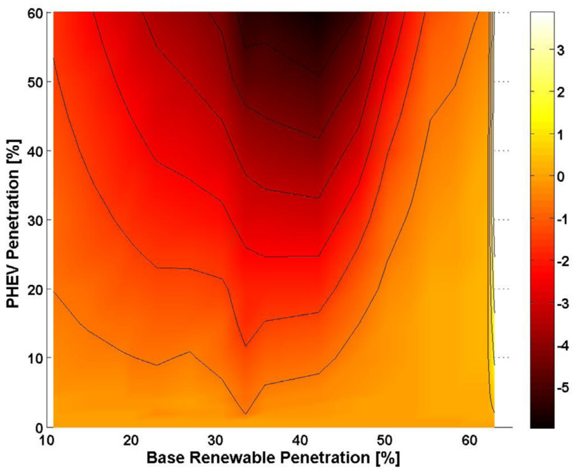

Fig. 4. Change in renewable penetration from the no-transportation case.

With regards to the integration of PHEVs, there are two competing forces that affect the change in renewable penetration from the base level.

First, the introduction of PHEVs onto the grid increases the overall electric load demand. For example, at a 60% PHEV penetration level with a 35 mile all-electric range, the energy of the electric load demand increases by 18.25%. This acts to decrease the renewable penetration level from the base value by increasing the denominator (E_{load}), since a given amount of delivered renewable energy will count for a smaller fraction of the total load.

Second, the integration of PHEVs with smart charging capability acts to smooth out the load profile to the extent possible, constrained by consumer requirements, charging power, and battery capacity. In this case, PHEV charging acts to add load during periods when the net load demand is low, and refrains from adding load when the net load demand is high. This behavior can prevent curtailment of renewable power during certain periods, and serves to increase the renewable penetration level from the base value since renewable energy that would otherwise have been curtailed would be allowed to serve the load demand.

In general, curtailment of renewable power can occur for a number of reasons. For example, when renewable power generation increases, the dynamic balancing generator fleet must turn down in power output. This can involve operating at part load conditions, or shutting down individual generators. There are limits to the extent to which this can occur, since some capacity of dynamic balancing generators must be online for reliability requirements, and these generators individually have minimum part-load operating limits due to emissions constraints. Additionally, base-load generators that are online cannot shut down or decrease power output quickly or to any large extent. If an increase in renewable generation is so large that it causes the net load demand to drop below the sum of the power output from base-load power plants and the minimum power level of the dynamic generator fleet, a portion of the renewable generation must be curtailed in order to maintain reliability and meet emissions requirements. Fossil fueled generators also have minimum operating times, for example, if a natural gas fired load-following plant is activated, on average it must operate for at least 8 h [27]. Additionally, if the net load decreases more quickly than the ramp-down capability of the dynamic balancing generator fleet, renewable generation may have to be partially curtailed. The integration of PHEVs with smart charging acts to prevent these effects. When the net load is low during periods of high renewable generation or simply low stationary demand, vehicle charging load can be added. This acts to increase the numerator ($E_{\text{Ren,delivered}}$), by allowing more of the renewable energy to serve the load demand.

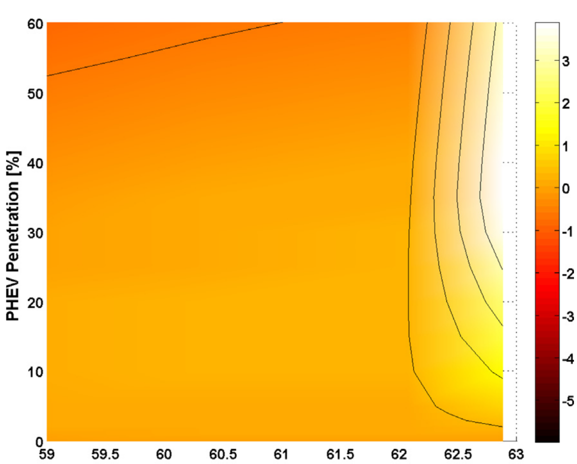

Fig. 5. Change in renewable penetration from the no-transportation case (inset).

With those forces in mind, the behavior of the change in renewable penetration shown in Fig. 4 can be understood. For most of the base renewable penetration range considered here, the addition of PHEVs decreases the renewable penetration level from the base value because this region corresponds to low installed renewable capacity, and renewable generation is not large enough to cause significant amounts of curtailment. Therefore, the primary effect is to increase the energy of the load demand, with larger increases occurring with higher PHEV penetrations.

The larger decrease at base renewable penetrations between 30% and 45% and high PHEV penetration levels occur simply due to the fact that the renewable penetration level is more sensitive to additions of a constant load level at higher base levels from a difference standpoint. For example, consider the 60% PHEV penetration level which increases the energy of the load demand by 18.25% at the 10.7% base renewable penetration level and a load of 100 energy units:

$$\text{Rpen}_{\text{orig}} = \frac{E_{\text{Ren,delivered}}}{E_{\text{load,orig}}} = 10.7\% = \frac{10.7}{100}$$

$$\text{Rpen}_{\text{PHEV}} = \frac{E_{\text{Ren,delivered}}}{E_{\text{load,orig}} + E_{\text{load,PHEV}}} = \frac{10.7}{100 + 18.25} = 9.05\%$$

$$\Delta\text{Rpen} = \text{Rpen}_{\text{orig}} - \text{Rpen}_{\text{PHEV}} = 10.7\% - 9.05\% = 1.65\%$$

Now consider the same load added at a base renewable penetration of 30%:

$$\text{Rpen}_{\text{orig}} = \frac{E_{\text{Ren,delivered}}}{E_{\text{load,orig}}} = 30.0\% = \frac{30}{100}$$

$$\text{Rpen}_{\text{PHEV}} = \frac{E_{\text{Ren,delivered}}}{E_{\text{load,orig}} + E_{\text{load,PHEV}}} = \frac{30}{100 + 18.25} = 25.37\%$$

$$\Delta\text{Rpen} = \text{Rpen}_{\text{orig}} - \text{Rpen}_{\text{PHEV}} = 30.0\% - 25.37\% = 4.63\%$$

Therefore, the difference in renewable penetration from base is expected to be larger at higher base renewable penetrations when the first effect dominates.

As the base renewable penetration increases above the 45% mark, the second effect begins to be present. In these regions, the renewable capacity is large enough such that curtailment due to over-generation or quick ramping becomes substantial. The PHEV load in these cases is dispatched, through smart charging, during periods of high renewable power generation and is able to keep the net load above the sum of the power output from base-load power plants and the minimum power level of the dynamic generator fleet. This allows renewable energy that would otherwise be curtailed to be used to serve the load, and the decrease in renewable penetration from the base case starts to be reduced. The PHEV load is able to restore the renewable penetration level to base values.

At the very highest renewable penetration levels (above 60%), the renewable penetration level increases from the base value due to the effect of PHEVs. For the parameters considered here, the maximum increase in the renewable penetration level from base is +3.87%, increasing from 62.87% to 66.74% at a 35% PHEV penetration level. In these cases, however, there is a limit to the extent to which PHEV charging load dispatch can increase the renewable penetration level, since the renewable capacities can become so large such that the PHEV load is only able to reduce curtailment as opposed to prevent it. In general, the energy of the PHEV load is generally small compared to the energy obtained from renewable resources at high penetration levels, and is therefore limited in its ability to provide benefits. There is also an additional limitation due to the variable flexibility of the PHEV charging load. The use of home charging causes the majority of the charging load to be dispatched during the nighttime, when a large amount of vehicles are plugged into the grid and the residence time of these vehicles is typically long. This tends to complement wind power in California, but not solar power. Implementing the ability to charge at home and work was found to help alleviate this problem, but only slightly. This occurs since daytime charging reduces solar power curtailment but removes load from the nighttime hours and increases wind power curtailment since the energy of the PHEV load is fixed for a given PHEV penetration level. Overall, the use of PHEVs with smart charging can provide benefits for the electric grid renewable penetration level, but only under certain conditions. To obtain this benefit, the size and flexibility of the PHEV load must complement the behavior of renewable generation.

3.1.2. Behavior of the renewable VMT and gasoline usage

The interface of the electricity and light-duty transportation sectors in the context of renewable electricity also affects the renewable penetration of the light-duty transportation sector. Even when using electric vehicles, much of the energy used to provide this electricity is still sourced from fossil fuels. While a reduction in fossil fuel use does occur, the extent of this reduction will depend on the electric generation portfolio. As the renewable penetration level of the electric grid increases, the extent of this reduction can be more significant. Fig. 6 shows the vehicle-miles-traveled (VMT) that are actually fueled by renewable electricity.

With the 35 mile all-electric-range assumption, electricity could be used to fuel approximately 76.2% of the vehicle miles traveled in California if all vehicles were PHEVs according to the model results. Of that percentage, however, only a fraction would actually be powered by renewable electricity since only part of the electric energy obtained from the grid is renewable. For the cases considered in this analysis, the maximum renewable VMT is about 31.48%, with a 60% PHEV penetration and a 62.8% base renewable penetration level (66.2% actual). With 60% PHEVs, about 45.7% of all VMT is fueled by electricity, but only 66.2% of that electricity is renewable. This indicates that 78% of the vehicle-miles-traveled are still fueled by fossil fuels, with 23.6% attributed to coal and natural gas electricity, and 54.3% coming from gasoline or diesel. Therefore,

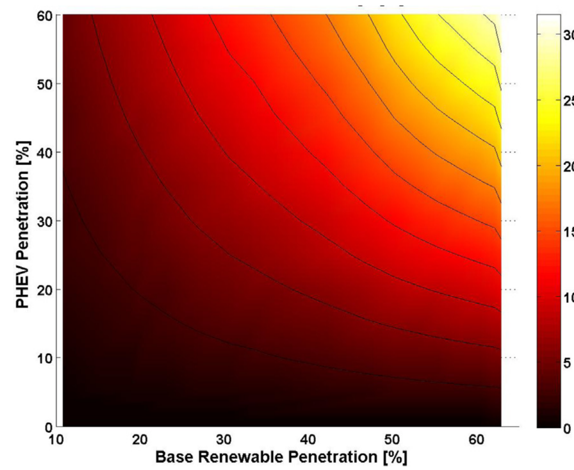

Fig. 6. Renewable VMT percentage.

PHEVs are highly reliant on the ability of the electric grid to reach high renewable penetration levels in order to operate on renewable energy. Furthermore, given the incredible cost of increasing renewable electricity penetration beyond 62.8% without reductions in base load capacity or the use of complementary technologies [17], it appears difficult to achieve transportation renewable usage beyond approximately 20% given the realistic vehicle and charging parameters considered here. These results confirm the need for additional alternatives for transportation such as hydrogen and biofuels.

On the other hand, the use of PHEVs does serve to linearly reduce gasoline consumption by shifting the transportation fuel mix towards coal, natural gas, and renewables. The latter are generally cleaner burning and more efficient from a primary energy conversion standpoint than the combustion of gasoline due to their centralized nature and ability to use extensive emissions cleanup equipment such as selective catalytic reduction (SCR). For PHEVs with a 35 mile all-electric-range, light-duty transportation sector gasoline usage decreases by about 0.77% for every 1% increase in PHEV penetration.

3.1.3. Behavior of the combined fuel usage and combined renewable fraction

Holistically, the effect of utilizing PHEVs and renewable electricity must be viewed by their effects on not just the grid alone or light-duty transportation sectors alone. These interactions must be viewed in the context of its sustainability goals and that of the combined sectors.

The change in the combined fuel usage of the electric and light-duty transportation sectors is presented in Fig. 7. The total energy usage is determined by combining the energy equivalent of all fuels used (coal, nuclear, natural gas, gasoline, etc…).

As the base renewable penetration and PHEV penetration level increases, the combined fuel use of both sectors decreases. This occurs due to the fact that electric vehicles are very efficient from a well-to-wheels perspective and are able to provide much more VMT per unit of input energy compared to gasoline vehicles.

Overall, however, the fuel use of the combined electricity and light-duty transportation sectors is more sensitive to base renewable penetration than PHEV penetration. This occurs because while using PHEVs may significantly decrease gasoline consumption and render the light-duty transportation sector more efficient, this is slightly offset by a small increase in grid fuel consumption, rendering the net decrease in fuel consumption smaller. In contrast,

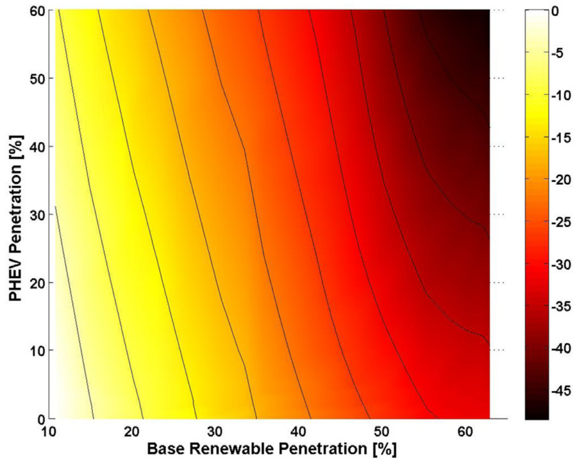

Fig. 7. Percentage change in combined fuel use of electricity and light-duty transportation sectors.

increases in the base renewable penetration level contribute wholly to reducing generation from non-renewable primary resources.

The greatest reductions in fuel usage occur when both the PHEV penetration and renewable penetration levels are increased, since these strategies complement each other. Increasing PHEV penetration levels reduce gasoline but increase grid load. Increasing renewable penetration complements this by reducing the fuel consumption of the electric grid per unit of load served, offsetting the increase in grid fuel consumption due to the addition of the PHEV load. Combined, large reductions in fuel use can be garnered. On an energy basis, reductions of nearly 49% can be obtained for the scenarios examined in this analysis.

This further highlights the benefit of taking advantage of synergies between sustainability initiatives in the transportation and electricity sectors to provide holistic benefits.

To further understand combined sector performance, the combined primary renewable fraction is examined. This metric is different than renewable penetration since it represents the fraction of the total primary energy use that is served by renewable energy as opposed to the energy of the electric load demand:

$$\mathrm{Rfrac}_{\mathrm{primary}} = \frac{E_{\mathrm{Ren,delivered}}}{E_{\mathrm{use,\ primary}}} = \frac{E_{\mathrm{Ren,delivered}}}{E_{\mathrm{fuel}} + E_{\mathrm{Ren,delivered}}}$$

Even in the electric sector alone, the primary energy use is larger than the energy of the electric load demand since fuel must be converted to electric energy to serve the load with a significant efficiency penalty. For example, consider a 1 GWh load which requires 1 GWh of generation to serve. With an example average grid efficiency of 35%, providing that generation consumes 2.86 GWh equivalent of primary energy in fuel. Therefore, a 10% renewable penetration would signify 0.1 GWh of renewable energy delivered in this case, which would only equate to a 3.95% primary renewable fraction! It is also important to note that this metric uses the renewable energy delivered as a representation of renewable energy utilization. While renewable energy resources are not 100% efficient from an input-to-useful energy basis, utilizing these resources does not require consumption of a practically finite resource. For calculating fuel use, fuel must be consumed only to obtain a fraction of its energy as useful output. In contrast, the losses from primary renewable energy input to renewable energy delivered (i.e. energy in the wind stream to energy obtained from a wind turbine) do not represent energy that is consumed by the electricity sector. Therefore, the delivered renewable energy is used directly.

The combined primary renewable fraction considers the primary energy use of the light-duty transportation sector in addition to that of the electric sector in the denominator of the definition provided previously. Overall, this metric represents what fraction renewable energy contributes to the total energy usage of both sectors combined, and is presented in Fig. 8.

At low base renewable penetration levels, the combined renewable fraction is primarily sensitive to changes in the installed renewable capacity. Increases in the base renewable penetration level represent increases in the delivered renewable energy and reduces the fuel consumption of the electric grid, which increases the combined renewable fraction. PHEV penetration only affects the combined renewable fraction in these cases by reducing the total energy consumption of the light-duty transportation sector and imposing a smaller increase in primary energy consumption in the electric sector. Additionally, at low to mid renewable penetration levels, all of the energy obtained from renewable resources is being used to serve the aggregate sectors and curtailment is at a minimum. Therefore, PHEV penetration does not significantly influence the combined renewable fraction at low base renewable penetration levels.

At higher base renewable penetration levels, the combined renewable fraction becomes sensitive to PHEV penetration level. In these cases, the balancing effects of PHEV smart charging prevents or minimizes renewable curtailment and increases the amount of renewable energy utilized by the aggregated sectors from the base value. With the scenarios considered in this analysis, the combined renewable fraction reaches a maximum of 26.55%.

The first characteristic to notice is that the magnitude of the combined renewable fraction is considerably smaller than the renewable penetration or the renewable VMT as presented previously, as explained prior. This also occurs since much of the transportation VMT and electric load is still met by fossil fuel sources, which are generally not highly efficient and therefore require large fuel inputs to meet a given electric load and/or VMT demand. Increasing the combined renewable fraction would require 1) increasing the efficiency of mechanisms that meet the VMT and electric load demand – vehicles and power plants, and 2) increasing the amount of energy obtained from renewable resources – not just those in the electricity sector, but even resources and pathways that move directly to serve the light-duty transportation sector.

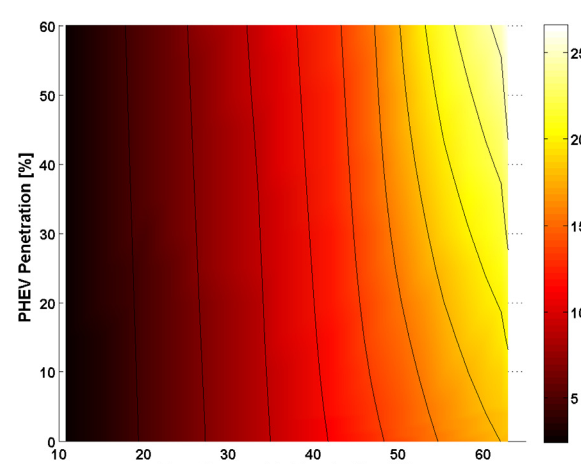

Fig. 8. Combined renewable fraction.

3.1.4. Behavior of the combined CO_2 emissions

Goals for reductions in CO_2 emissions should transcend the behavior of any individual resource sector and consider a holistic approach. It is not beneficial for one sector to increase CO_2 emissions in a manner that offsets reductions in another, and certain sectors have more potential for CO_2 reduction than others. For the electricity and light-duty transportation sectors, the reduction in combined CO_2 emissions from base 2005 levels (10.7% base renewable penetration) is presented in Fig. 9.

The combined CO_2 emissions of the electricity and light-duty transportation sectors are sensitive to both changes in base renewable penetration and PHEV penetration. Increasing either of these parameters decreases the fossil fuel usage of their respective sectors, which results in CO2 emissions reductions. The sensitivity due to PHEV penetration, however, is affected by the following parameters: 1) only a certain fraction of the VMT met by PHEVs is actually fueled by electricity and 2) the decrease in gasoline use for PHEVs is slightly offset by the corresponding increase in fossil fuel usage on the electric grid. In contrast, increasing the renewable electricity penetration level translates directly to decreased fossil fuel usage for the electricity sector.

When examining the sensitivity of CO_2 emissions from these sectors, however, the sensitivity to PHEV and renewable penetration is somewhat different. While the electric grid uses a similar amount of fuel on a primary energy basis, it emits less CO_2 compared to the light-duty transportation sector. This occurs due to differences in efficiencies and the composition of the fuel stream for each sector. The electric grid uses a variety of fuel types. Primary fossil fuel types are coal and natural gas, with the latter being the dominant fuel source for California and emitting a relatively low amount of CO_2 per MMBTU of fuel input. Other types are also present which emit much smaller CO_2 amounts such as biomass and biogas, and many other types such as nuclear, wind, solar, geothermal and hydropower emit negligible CO_2 per unit of useful electrical energy obtained. Therefore, the electric grid is able to use a larger amount of primary energy with lower CO_2 emissions.

The light-duty transportation sector, in contrast, uses one primary fuel source to meet essentially the entirety of the VMT demand: gasoline. Gasoline emits a higher amount of CO_2 per unit of useful energy obtained compared to natural gas. The conversion pathway from primary energy to useful motive energy is also generally less efficient compared to the pathway from primary energy to useful electric energy in the grid. Therefore, while the light-duty transportation sector uses a lower amount of primary energy, it exhibits higher CO_2 emissions.

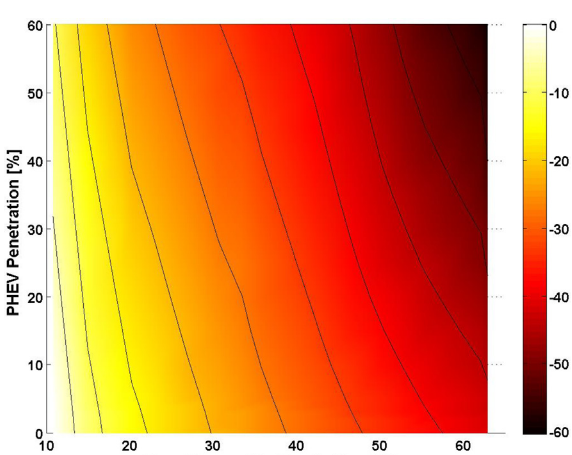

Fig. 9. Percentage change in combined CO_2 emissions.

Therefore, increasing the percentage of VMT that is met by electricity will cause a large reduction in CO_2 emissions for the light-duty transportation sector. However, when examining the combined transportation and electricity sectors, the increased fuel consumption placed on the grid due to PHEVs limits the net CO_2 reduction because the grid mix is still highly reliant on fossil fuels. This is evident from limited reductions due to PHEV penetration increases at low base renewable penetration levels. At the 10.7% base renewable penetration level, increasing the PHEV penetration level to 60% reduces the combined sector CO_2 emissions by 10.3% compared to the no-PHEV case. At the 62.8% base renewable penetration level, the same increase in PHEV penetration reduces the combined sector CO_2 emissions by 60.3% compared to the no-PHEV case at that penetration level. Once the grid mix shifts more towards low CO_2 emitting sources, the CO_2 benefits of PHEVs are maximized.

4. Conclusions

This study performed an examination of the effectiveness of PHEVs with smart charging in supporting the achievement of holistic CO_2 reduction, fossil fuel use, and sustainability goals with specific attention to aiding the increased integration of renewable resources onto the electric grid. The energy system of the state of California was used as the primary example of a system with large electric load and vehicle-miles-traveled demands. The key conclusions of this study are as follows:

1. The integration of PHEVs with smart charging can increase the utilization of installed renewable resources, but only under certain conditions. Since wind and solar power resources are peak-dominated, high capacities of these resources need to be installed to increase the renewable penetration level. At a certain point, capacities will become high enough to warrant curtailment of renewable generation. The introduction of the PHEV charging load allows the system to alleviate the effects of curtailment by placing load during periods of high renewable generation to some extent. This effect has benefits for increasing the actual renewable penetration level and combined renewable fractions. To obtain this benefit, however, the size and flexibility of the PHEV load must complement the behavior of renewable generation.
2. The electrification of the light-duty transportation sector through the use of PHEVs can contribute to reductions in combined sector fuel usage and CO_2 emissions, but the extent of these benefits depends on the progress of the grid towards reaching renewable energy procurement goals. The use of PHEVs in the light-duty transportation sector reduces fuel use and CO_2 emissions of the sector due to increased vehicle efficiency pathways and reductions in the amount of vehicle-miles-traveled fueled by gasoline. However, these reductions are slightly offset due to increasing the load demand on the electric grid. When renewable penetration levels are low, the electric grid relies heavily on fossil fuels that emit CO_2 and other non-renewable resources. Therefore, introducing PHEVs onto the grid when renewable penetrations are low causes an increase in the CO_2 emissions and fuel use of the electricity sector, slightly offsetting reductions in the transportation sector. Introducing too many PHEVs too early can exacerbate this effect.
3. In the holistic scope, environmental benefits due to the use of PHEVs are maximized when synergies between the deployment of these vehicles and that of renewable power generation are considered. Benefits for CO_2 emissions, fuel use, and renewable energy utilization are most significant when both PHEVs and renewable resources on the grid were deployed. This highlights

the importance of considering the interaction between sustainability measures in different sectors in a holistic sense.

Overall, PHEVs with smart charging can contribute towards meeting holistic environmental goals, but the simultaneous implementation of other complementary technologies will likely be required to actually meet those goals. Similar to other complementary technologies, the use of PHEVs has advantages and disadvantages. Limitations exist on the ability of PHEV smart charging that prevent its use from enabling the electricity and light-duty transportation sectors to meet the entirety of their holistic environmental goals. Therefore, other technologies such as demand response, energy storage, and other dispatchable loads will likely be required in tandem to make up the difference, and coordination between these technologies will be critical. Since the light-duty transportation sector has typically relied on a single paradigm, however, the advantages and disadvantages of PHEVs in this context will need to be compared against other technologies such as hydrogen fuel-cell vehicles on a consistent basis. The use of other PEV types, such as battery–electric vehicles (BEVs) and PHEVs with a different chemical fuel such as hydrogen will also need to be considered.

Part 2 of this study examines the benefits and disadvantages of introducing increased renewable capacities and PHEVs onto the electric grid from the standpoint of the design and operation of electric load-balancing resources in the system. The electric grid and all of its components operate under constraints which are imposed for the system to operate reliably and perform its stated function. Renewable generation and PHEVs can impact how these components need to be designed and operated.

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